Atoms as qubits

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Ingredients for QIPC

- **Quantum degrees of freedom**
- Local operations
- Measurements
- One of
  - Entangled state sources
  - Universa 2qb unitaries
- Error correcting schemes
- Large number of qubits

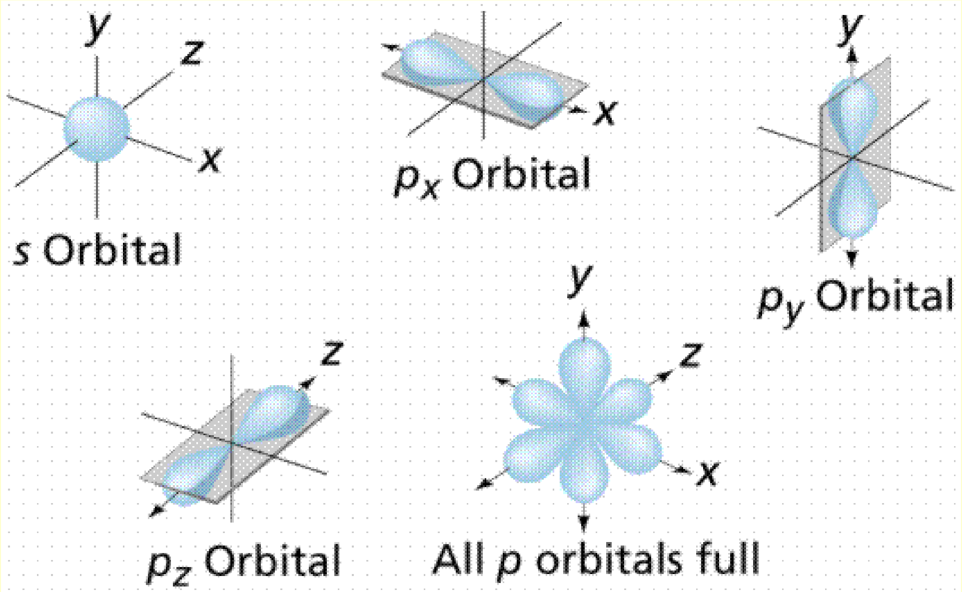
Q. Communication

Q. Cryptography

Q. Simulation

Q. Computation

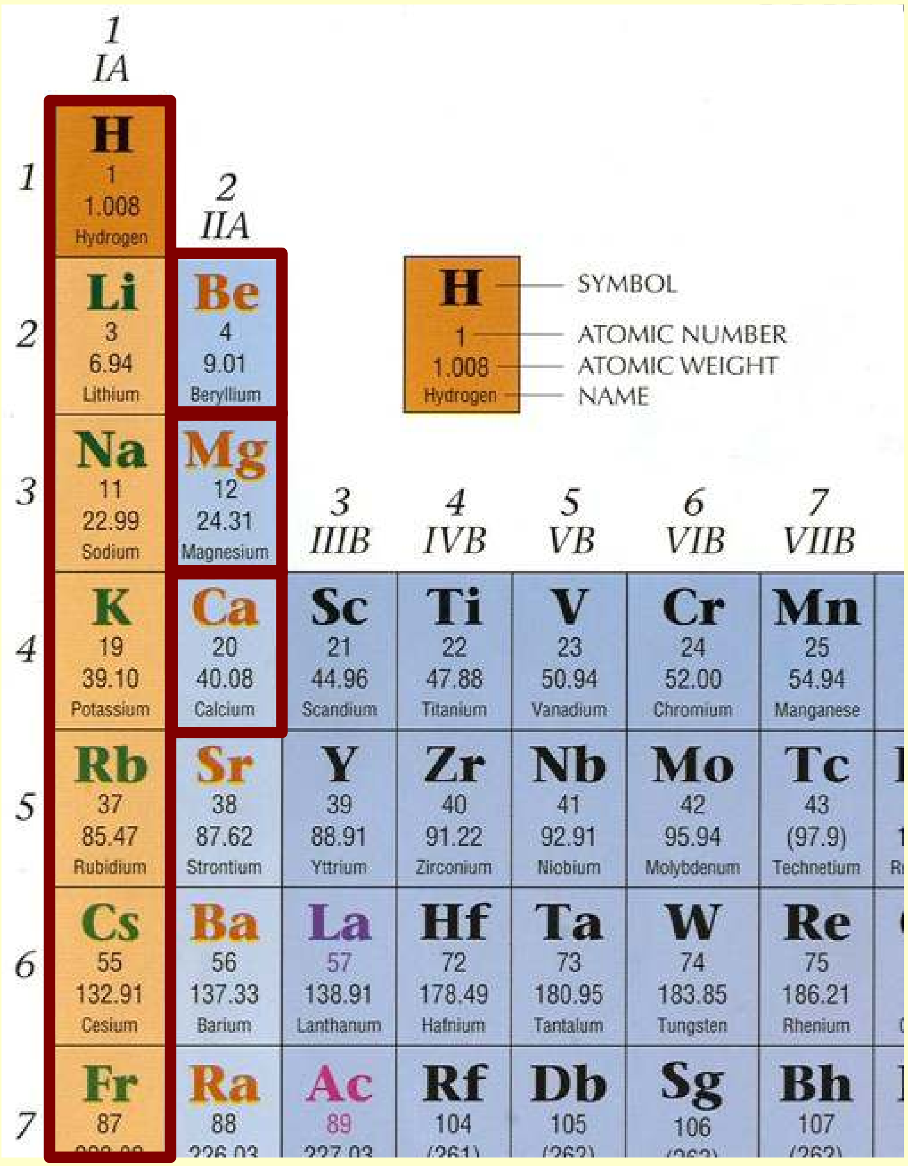
Atoms



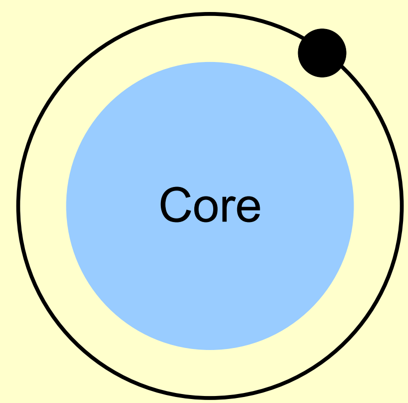
- We plan to use atoms as quantum registers.
- We have a variety of degrees of freedom to choose from
  - Electronic orbitals
  - Angular momenta
  - Electron spin
  - Nuclear angular momenta
  - Atom position/momentum
  - Collective many-atom states

  ...

Atoms

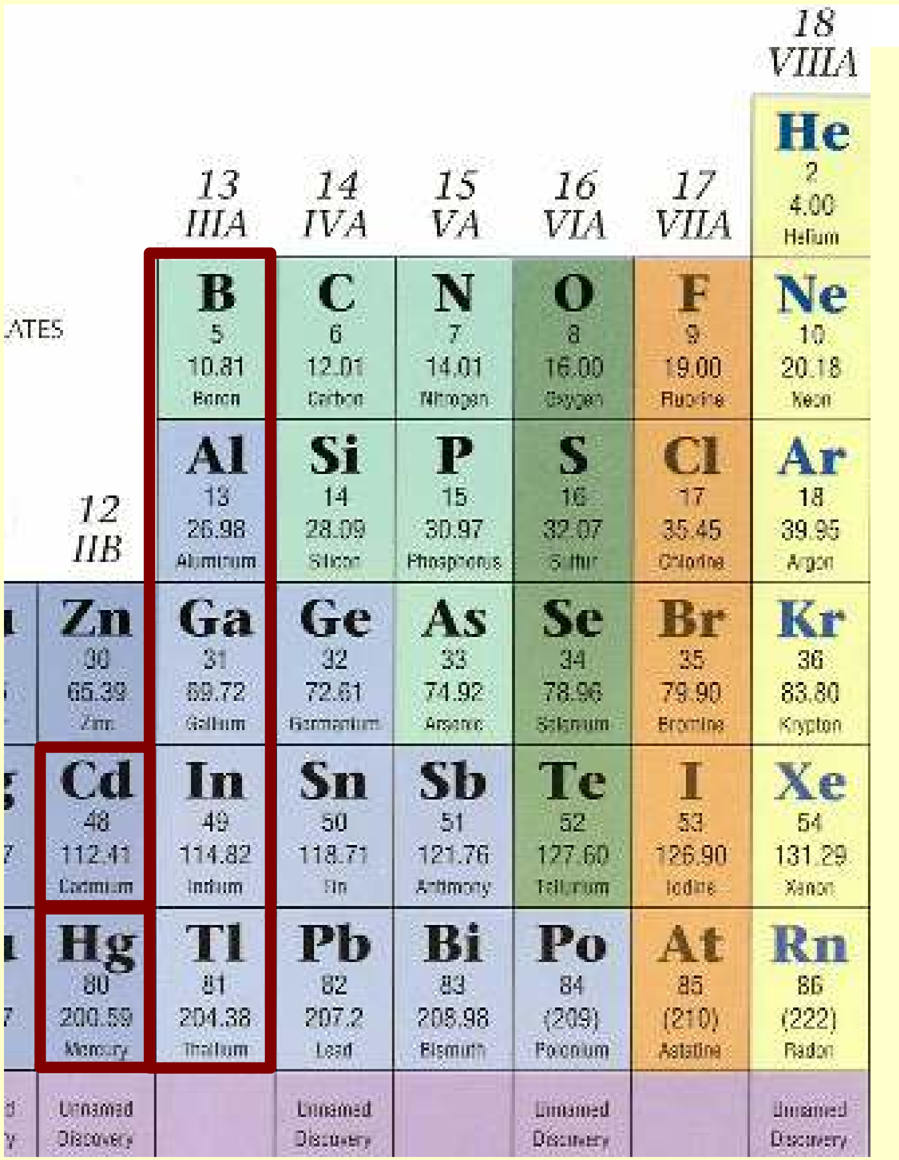


- It is convenient to focus on atoms with onely one valence **e⁻**
- This includes all hydrogen-like atoms



both neutral and some ions: $^{40}Ca^{+}$, $^{25}Mg^{+}$, $^{9}Be^{+}$, ...

Atoms



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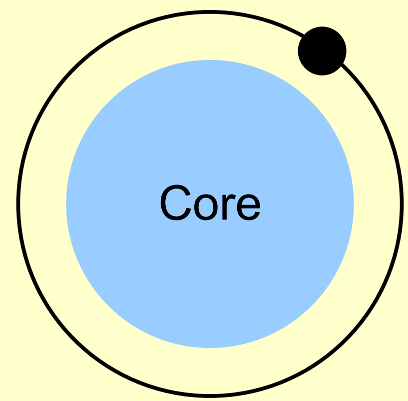
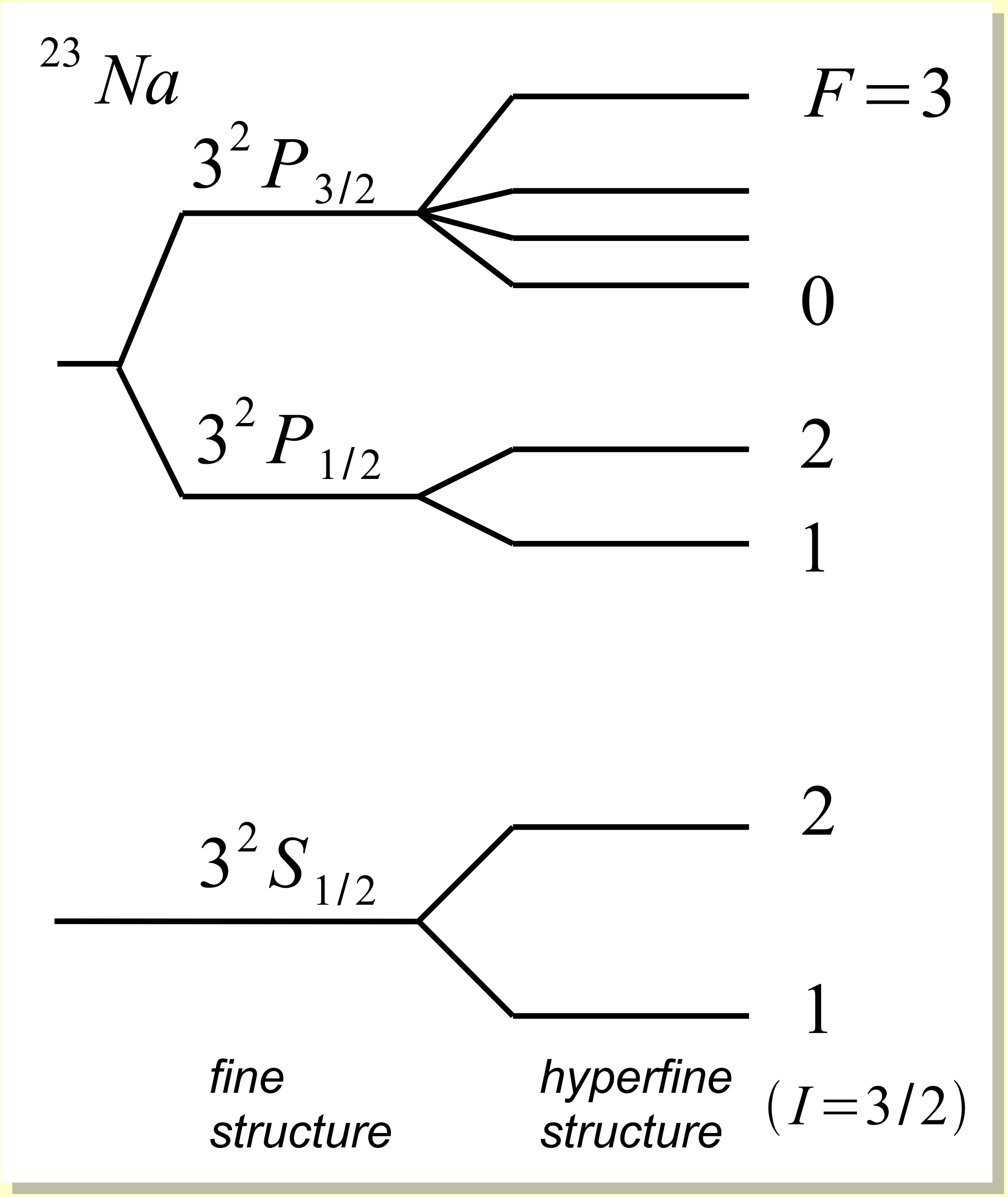


both neutral and some ions: $^{40}Ca^{+}$, $^{25}Mg^{+}$, $^{9}Be^{+}$, ...

Atomic levels

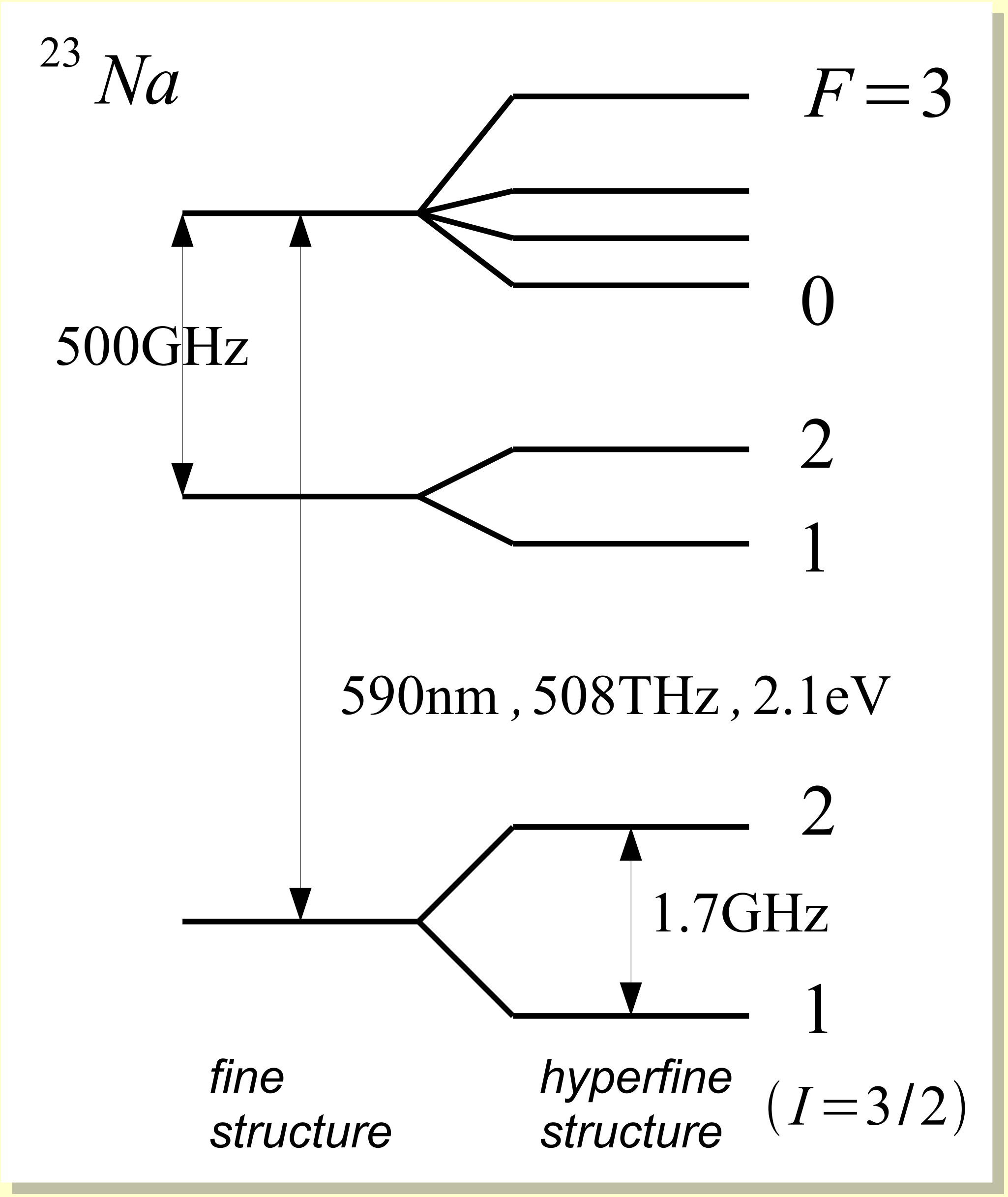


- The basic electronic levels are named

$$n^{2S+1}L_J$$

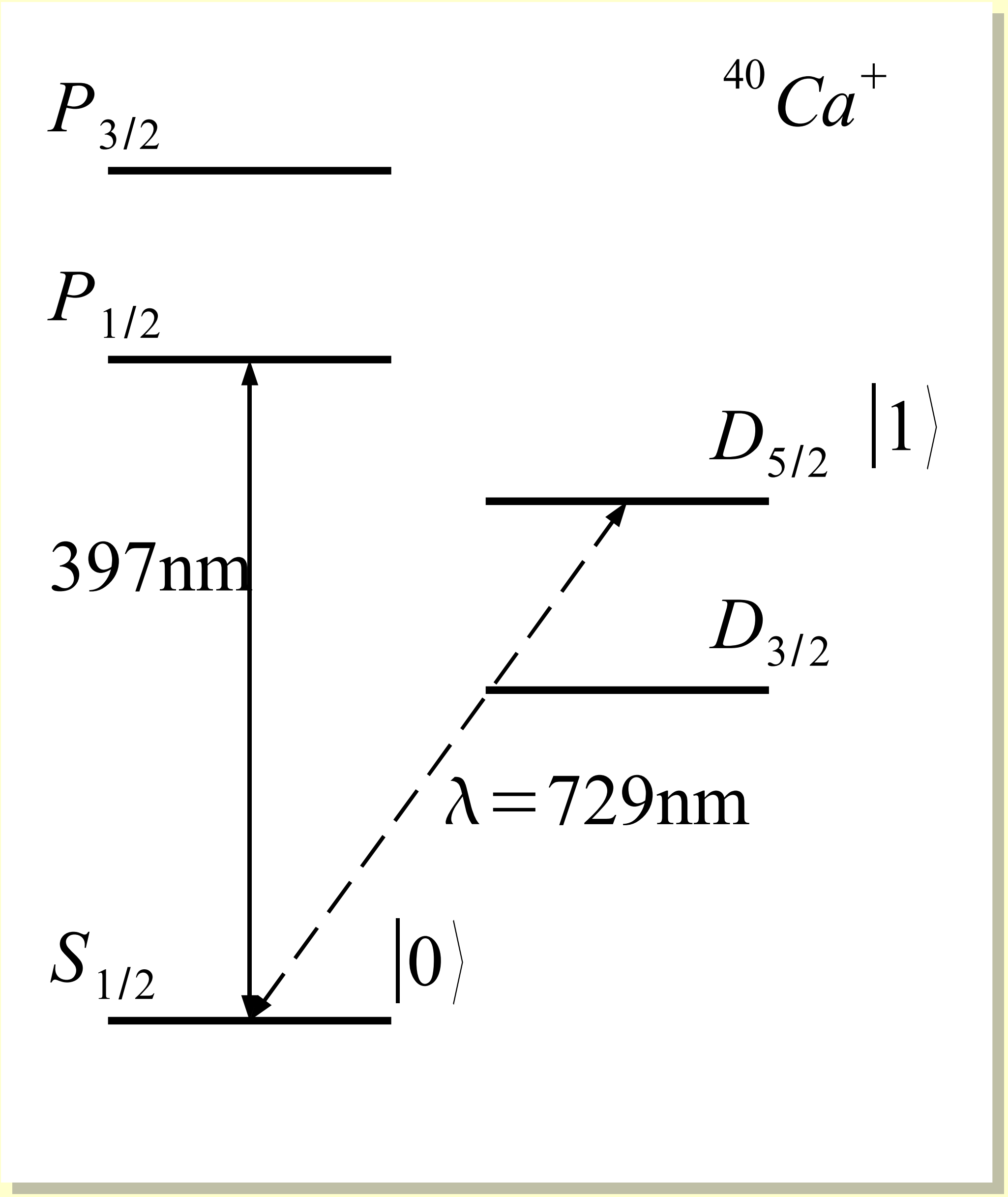
  - n = principal Q number
  - **L** = orbital angular momentum
  - **S** = spin
  - **J = L + S**
  - I = nuclear ang. momt.
  - **F = L + I**

Atomic levels



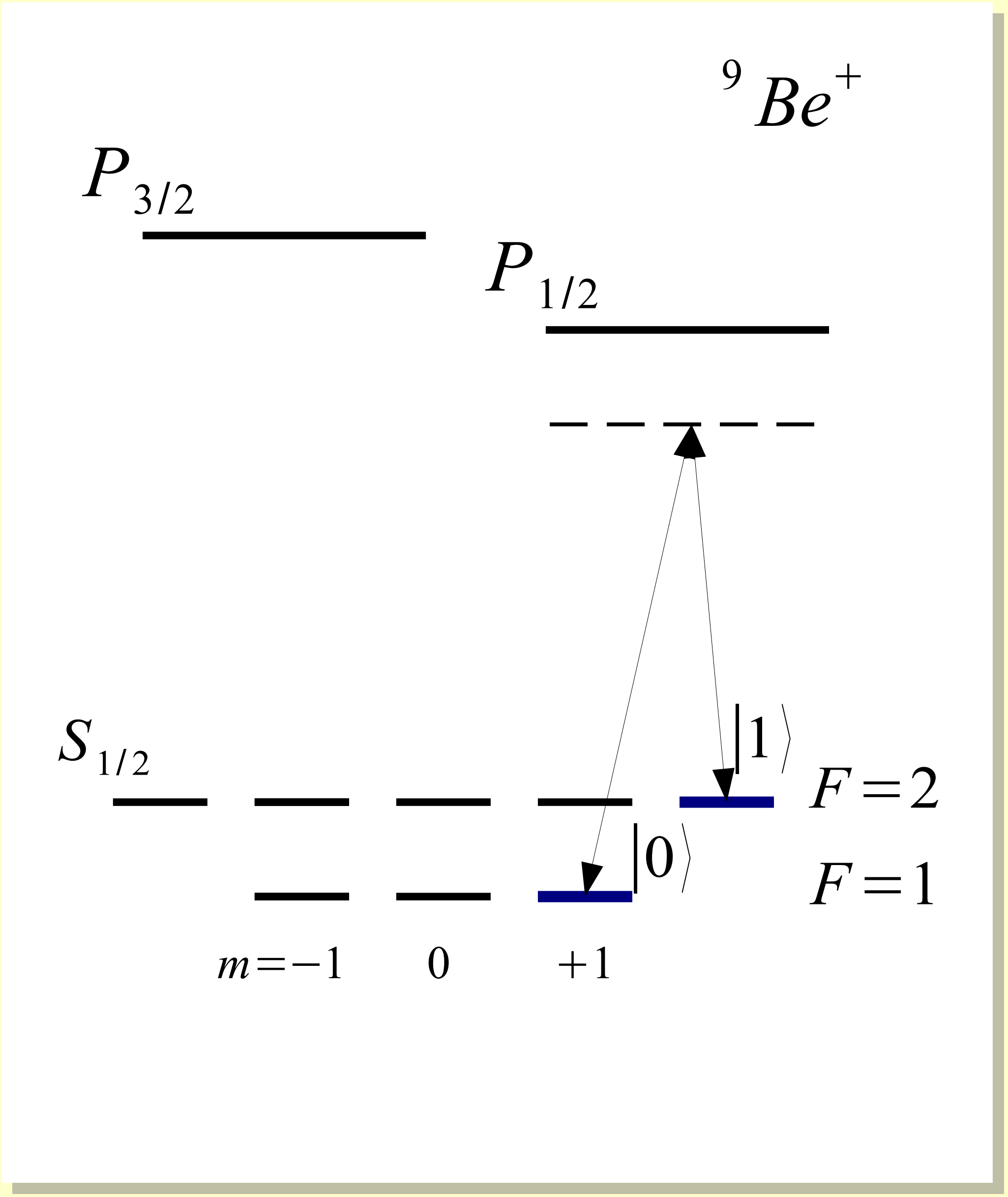
- We get a lot of different energy separations:
  - Optical
  - Energetic microwave
  - Long microwaves
- Not all transitions are permitted
  - $\Delta M = 0$ (π), ± 1 ($\sigma^{\pm}$)
  - $\Delta L = \pm 1$
  - ΔJ, $\Delta F = 0, \pm 1$

Excited state encoding



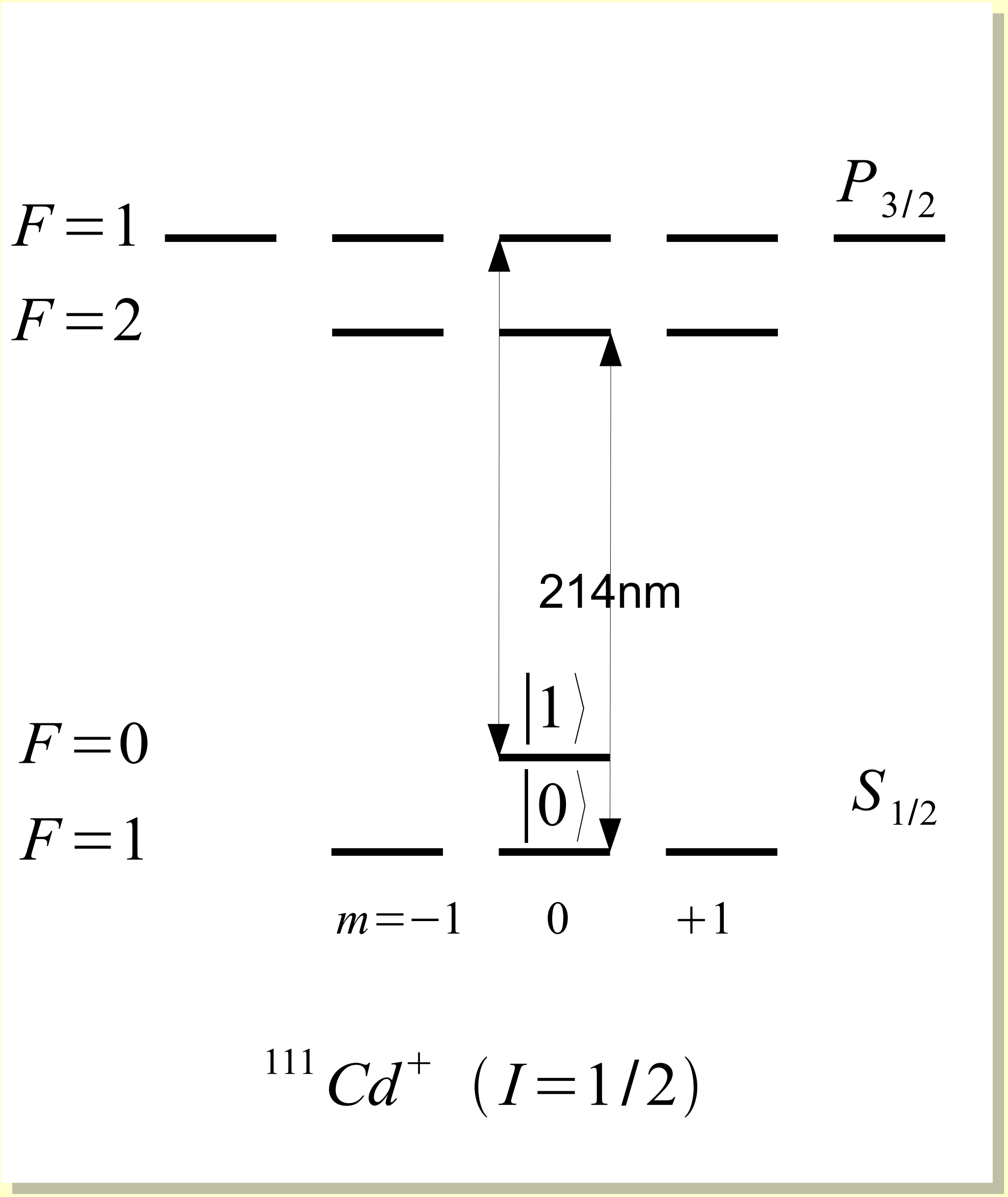
- The $^{40}Ca^{+}$ ion is used in the experiments from Innsbruck
- The qubit is encoded in a ground and an excited state.
- No hyperfine splitting.
- The excited state is metastable but long lived 1.5s
- For this the 0-1 transition can not be dipole-allowed
  - Second order processes
  - Strong lasers

Hyperfine encoding



- The $^9Be^+$ ion is used in the experiments from NIST.
- The qubit is encoded in two hyperfine ground states
  - No decay
- States have to be coupled using either
  - Microwave (delicate)
  - Raman transitions
- The choice of states is still sensitive to magnetic fields.

Hyperfine encoding

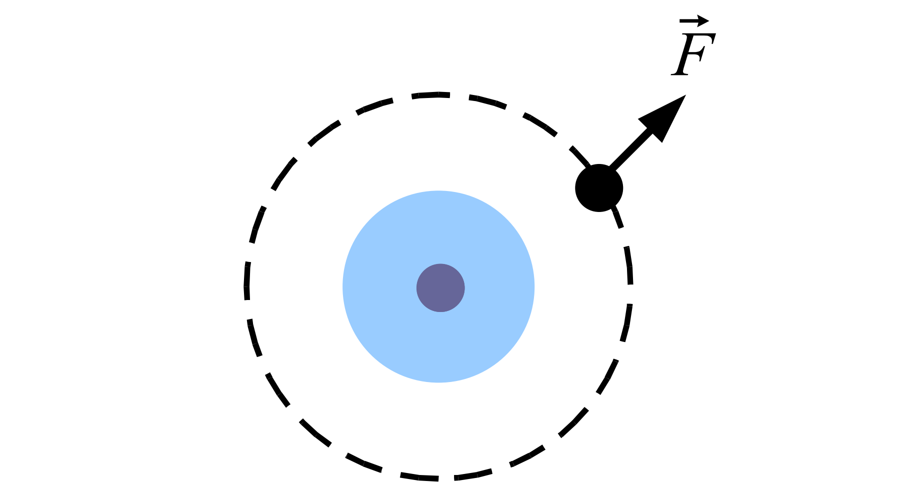


- A variant being used in Maryland (Monroe).
- The qubit is stored in hyperfine states.
- Now m_F=0, so that coupling to magnetic fields can be prevented.
- The advantange is ultrashort transitions to excited states

Atom manipulation

Atom-light interaction

$$\vec{E}(x,t) \sim e^{i(kx-\omega t)}$$

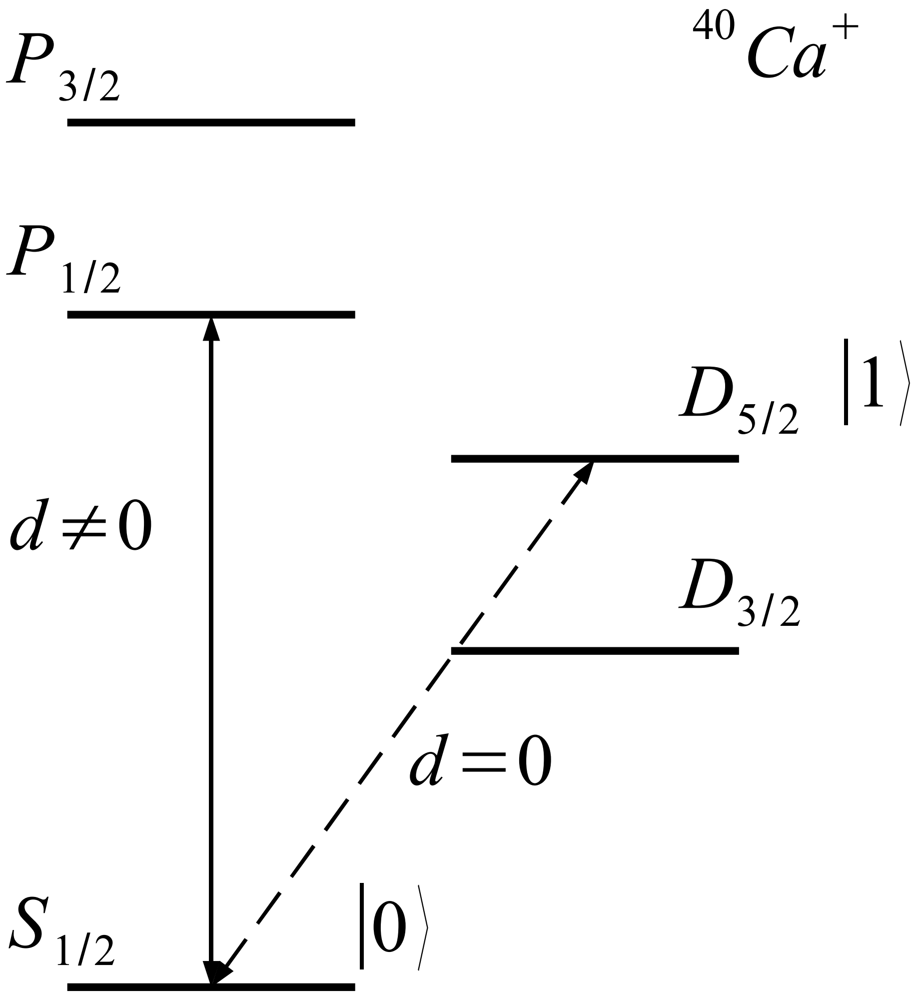


$$\lambda \gg a_0, E(x,t) \sim E(R_{CM},t)$$

- The atom sees the wave as an oscillating potential.
- We can treat the problem as
  - A light electron
  - trapped by a heavy core
  - subject to a force
- Dipole coupling Hamiltonian

$$H = H_{core} + H_{light} + \frac{\vec{p}_e^{\,2}}{2m} + V_e(\vec{x}) + \vec{d} \cdot \vec{E}$$

Atom-light interaction



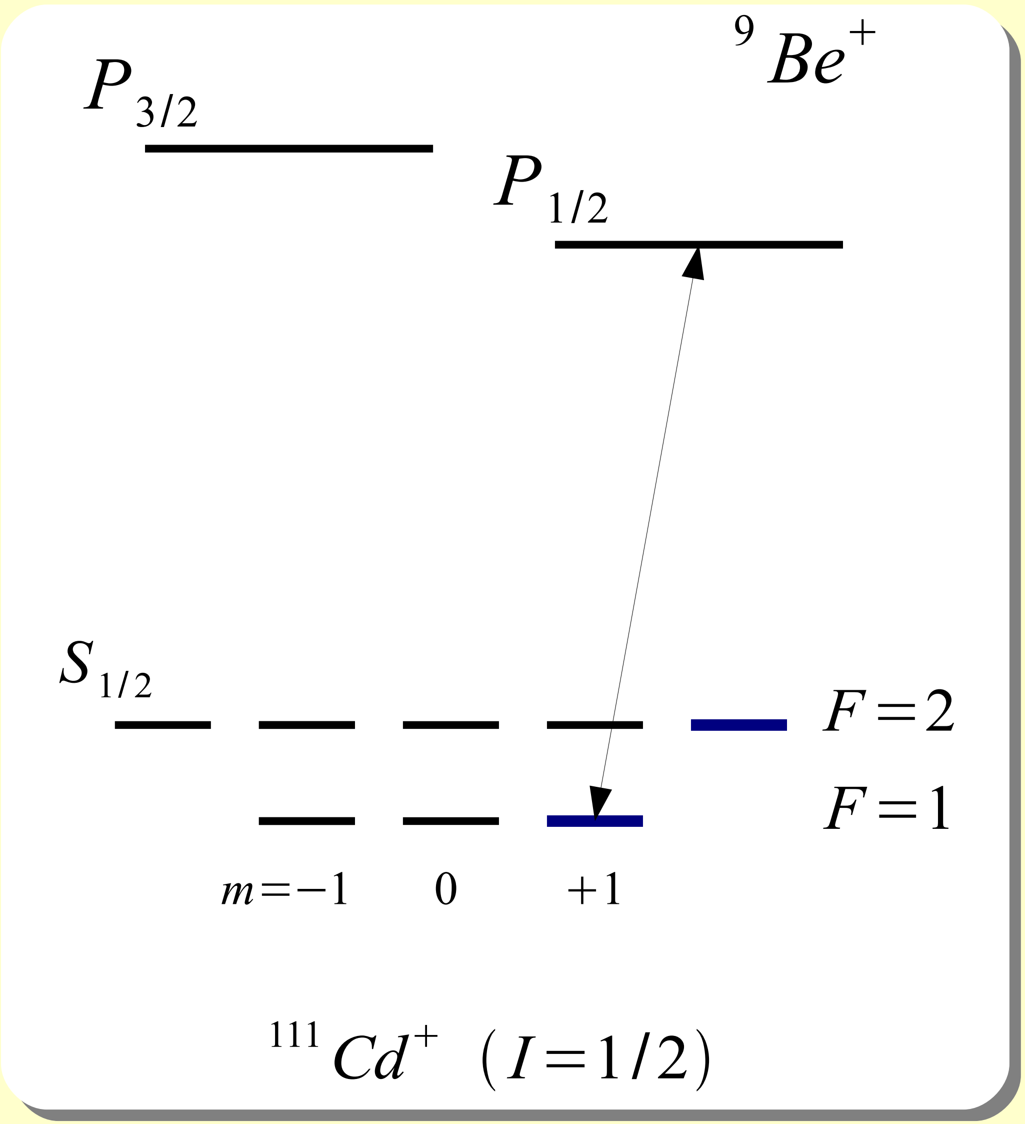
- First we diagonalize everything but the coupling

$$H = \sum_{nFm_F} E_{nFm_F} |nFm_F\rangle\langle nFm_F| + \sum_{\omega} \hbar\omega\, a_\omega^{+} a_\omega + \vec{d} \cdot \vec{E}$$

- The dipole moment only has elements between different states

$$\vec{d} = \sum d_{ge} (|e\rangle\langle g| + |g\rangle\langle e|)$$

Atom-light interaction



- The coupling ends up in the form

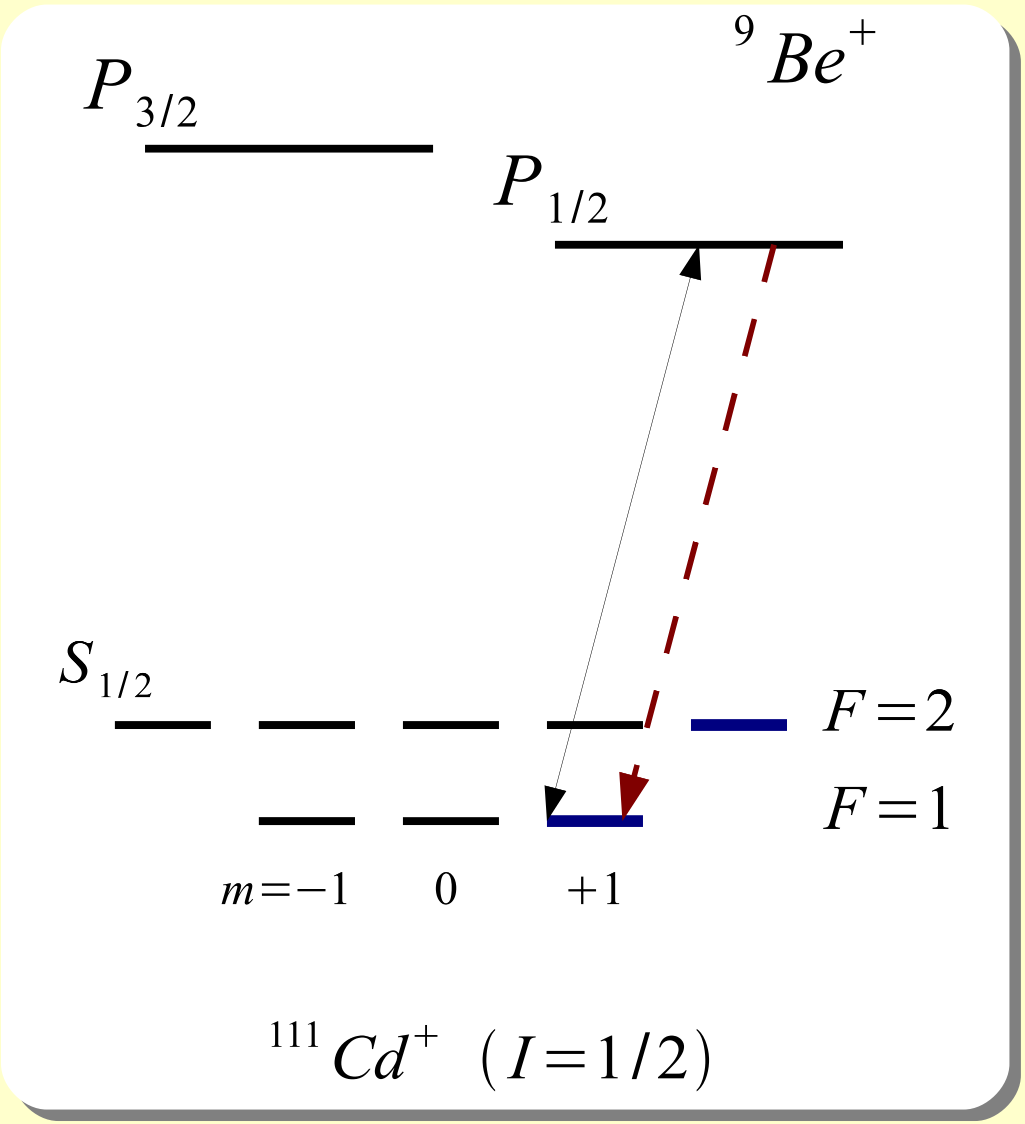
$$H_{dip}=\Omega\left(|e\rangle\langle g|+|g\rangle\langle e|\right)\times \times\left(a^{+}+a\right)$$

- For long times, the energy nonconserving terms can be neglected

$$H_{RWA}=\Omega\left(|e\rangle\langle g|a+a^{+}|g\rangle\langle e|\right)$$

RWA = rotating wave approximation

Spontaneous emission



- There are other coupling channels

$$H_{dip} = \sum_{k \neq k'} \Omega \left(|e\rangle\langle g| + |g\rangle\langle e| \right) \times$$
$$\times \left(a_k^+ + a_k \right)$$

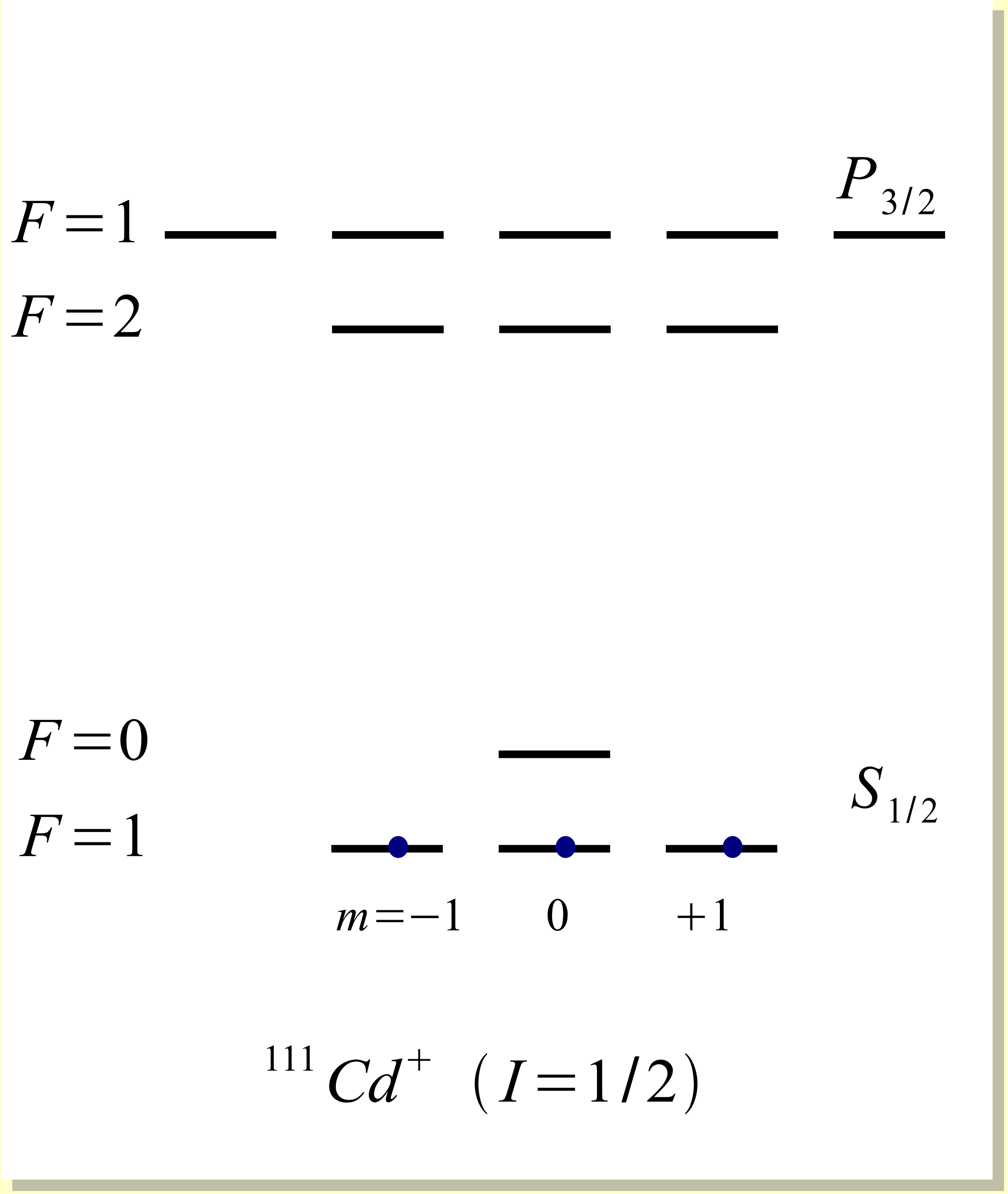
- Atom emit into **different** modes from absorbed photon
- When tracing out the lost photons, decoherence

$$\rho \rightarrow (1-\varepsilon)\rho + \epsilon \sigma^- \rho \sigma^+$$

Quantum register preparation

Quantum register preparation

- An essential step in the quantum computation.
- We do not need to prepare an arbitrary state.
- We just need to **reset** the ions to the **same state** and use unitaries.



Optical pumping

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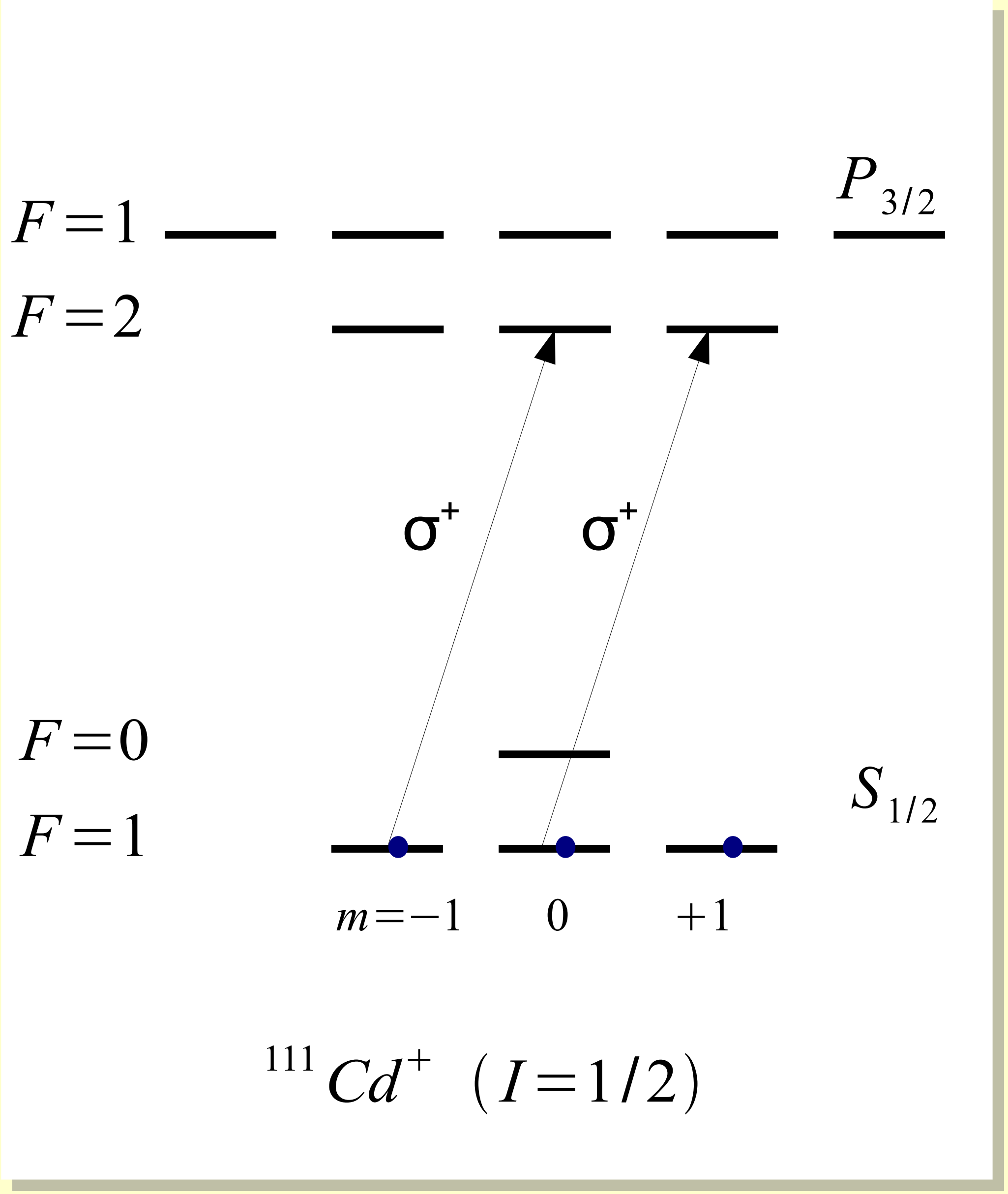
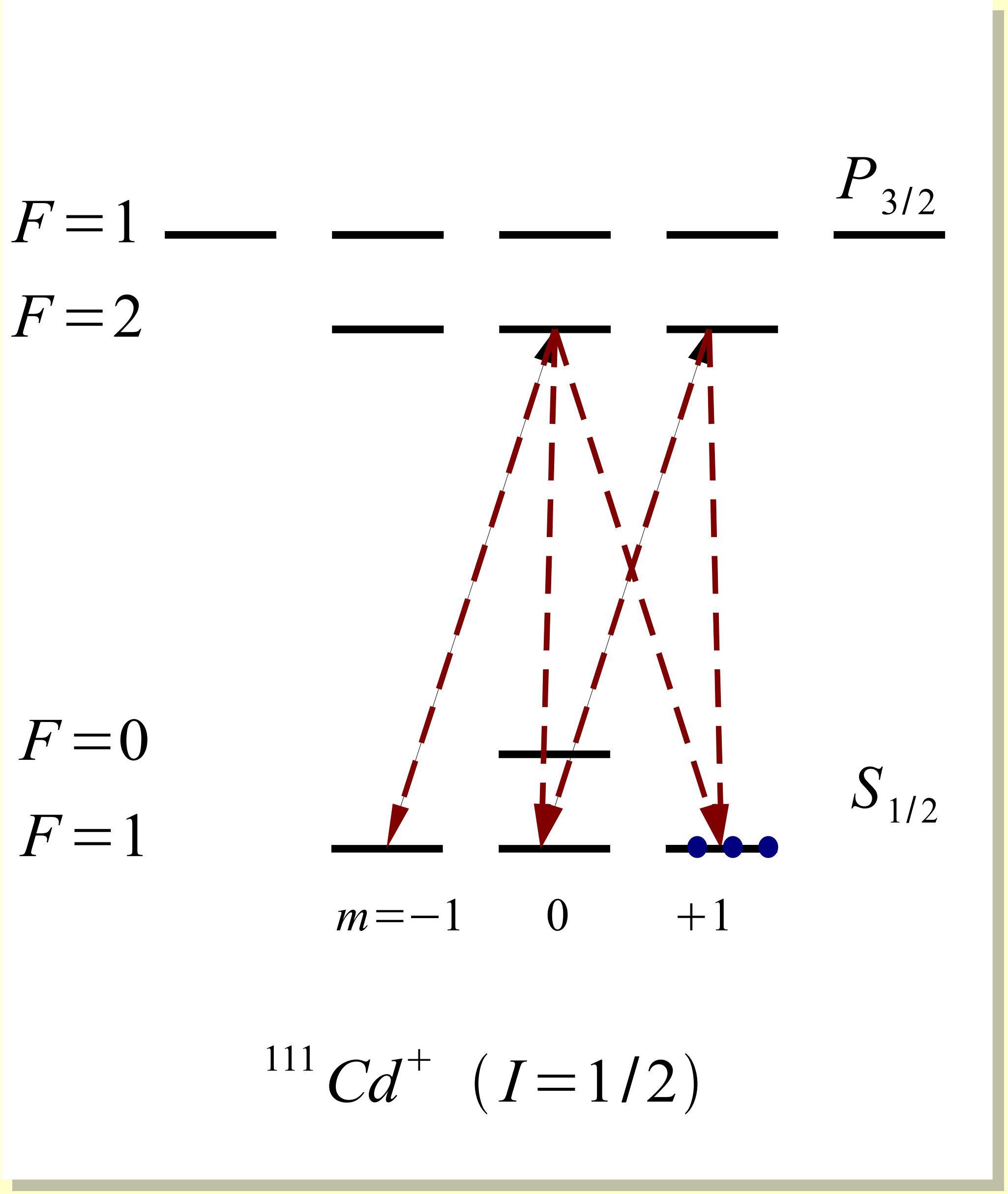
- We pump atoms with the same polarization, σ^+



Optical pumping

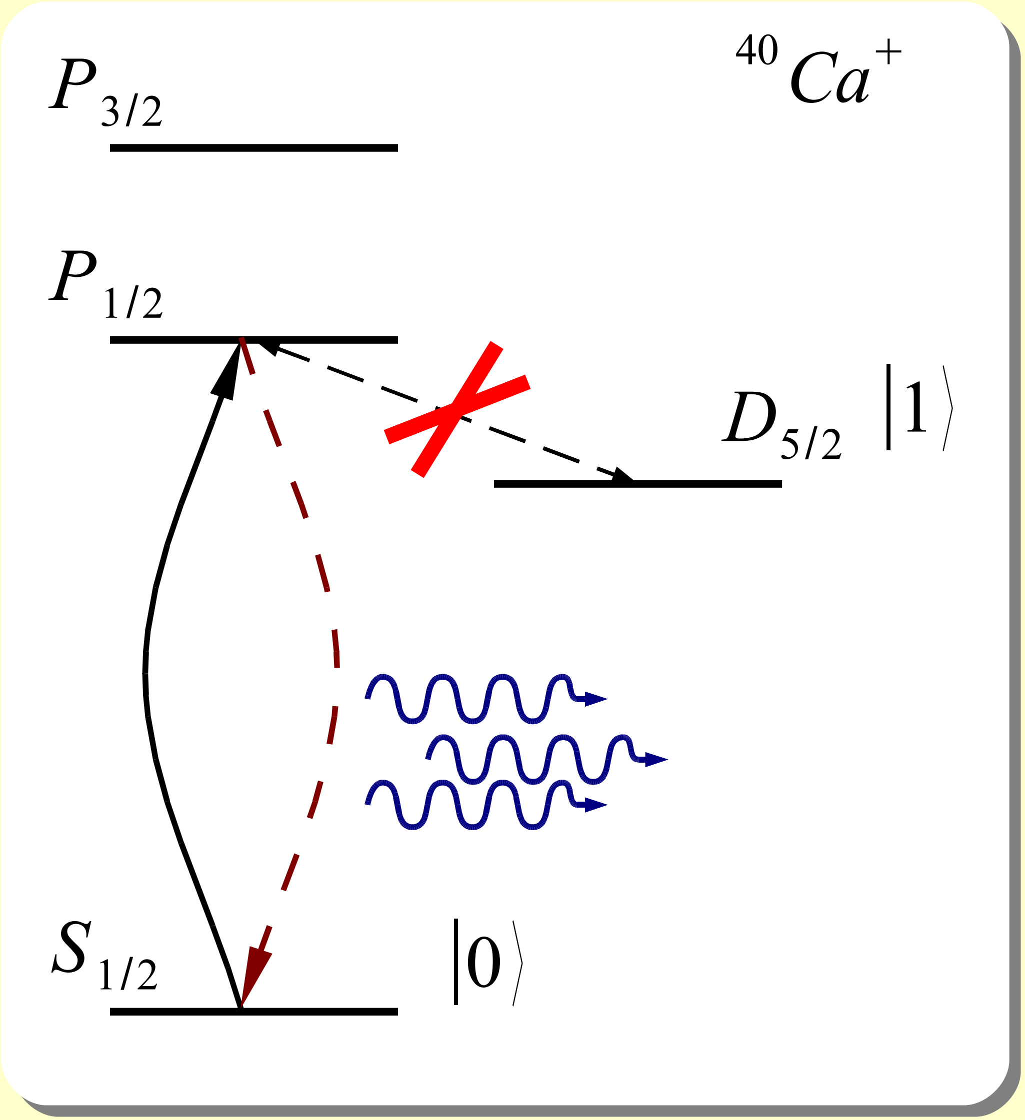
- An essential step in the quantum computation.
- We do not need to prepare an arbitrary state.
- We just need to **reset** the ions to the **same state** and use unitaries.
- We pump atoms with the same polarization, σ^+
- A fraction of the atoms decays with smaller m_F
- Total net flow towards m_F=+1



Measurements

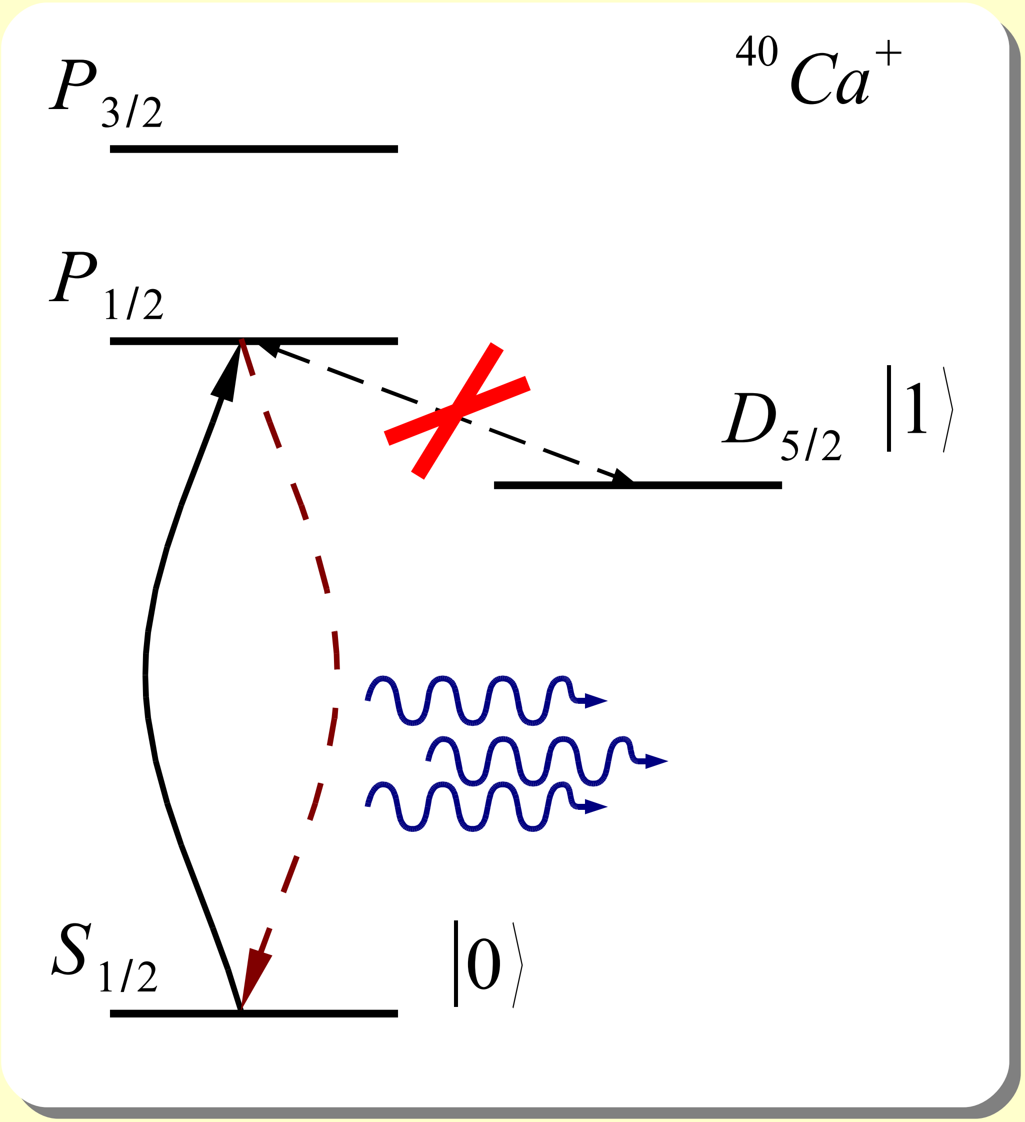
Measurement

- A process to accurately distinguish the qubit 0 and 1.
- **Electron shelving**
  - Pump the 0 state to an auxiliary state.
  - The transition is forbidden for the 1 state.
  - The excited state decays emitting photon
  - Repeat until enough photons are gathered.



Measurement

- Projective measurement
  - Atom ends up in 0 or 1
  - It can be repeated indefinitely.
- Lots of photons compensate for bad detector efficiency
  - Almost 100% accuracy
  - Best qubit measurements ever!
- Better done at the end
  - Scattered photons may affect neighboring atoms.



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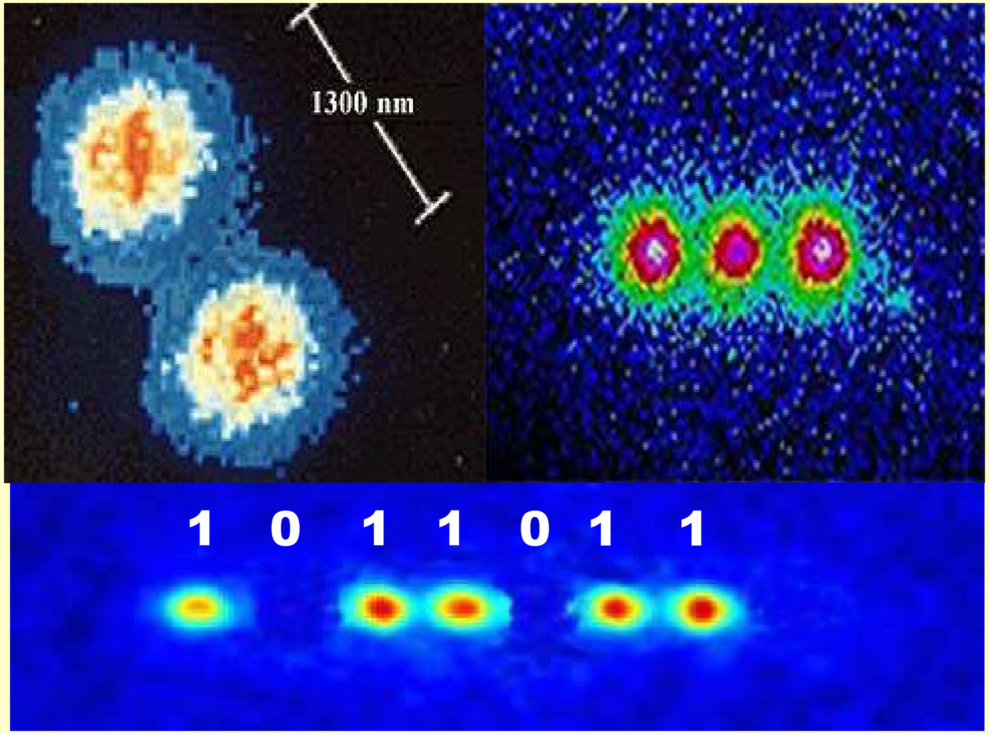
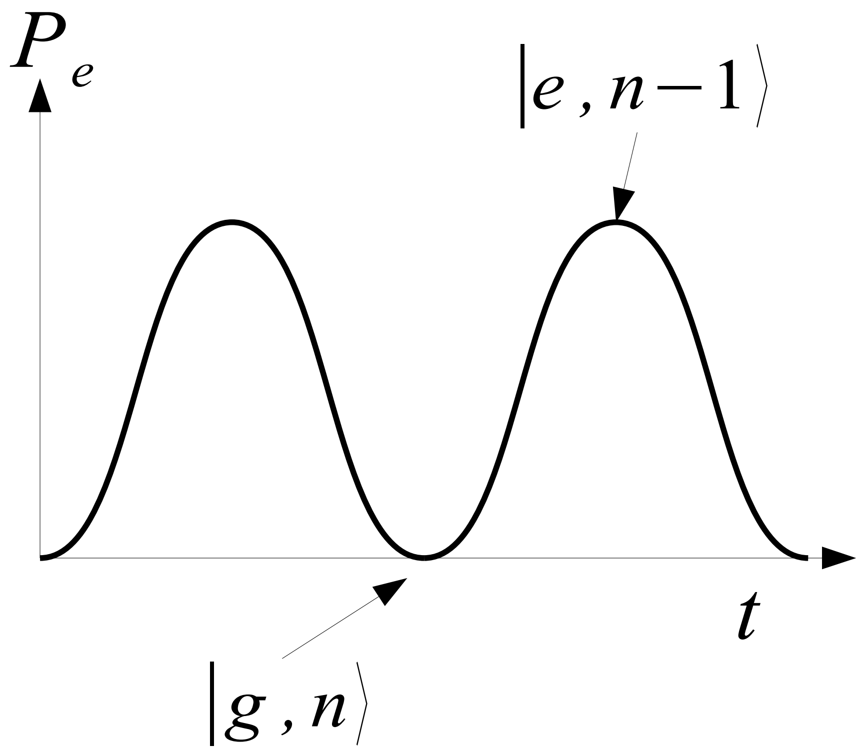


Single qubit rotations

Rabi oscillations

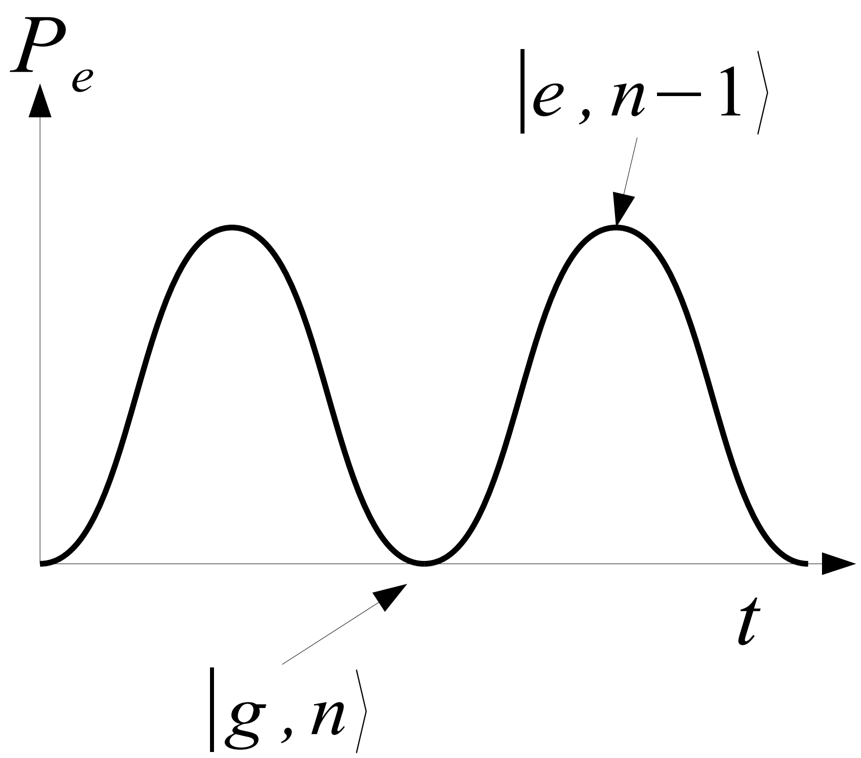


- An ideal but realistic case is when only two levels are coupled:

$$H_{RWA} = \omega_a \sigma_z + \omega_l a^+ a + \\ + \Omega \left(|e\rangle\langle g| a + a^+ |g\rangle\langle e| \right)$$

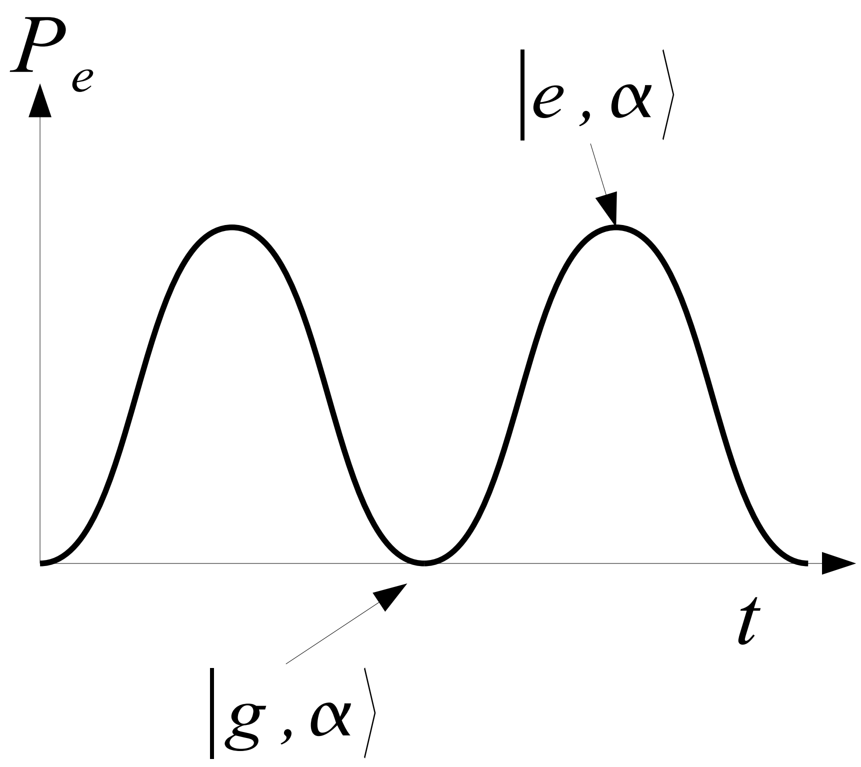
- Physical parameters
  - Detuning $\delta = \omega_l - \omega_a$
  - Rabi frequency Ω
- Integrable, oscillations between ground and excited state.

Rabi oscillations



- Not useful for doing qubit gates: Light and atom are **entangled**.

Rabi oscillations



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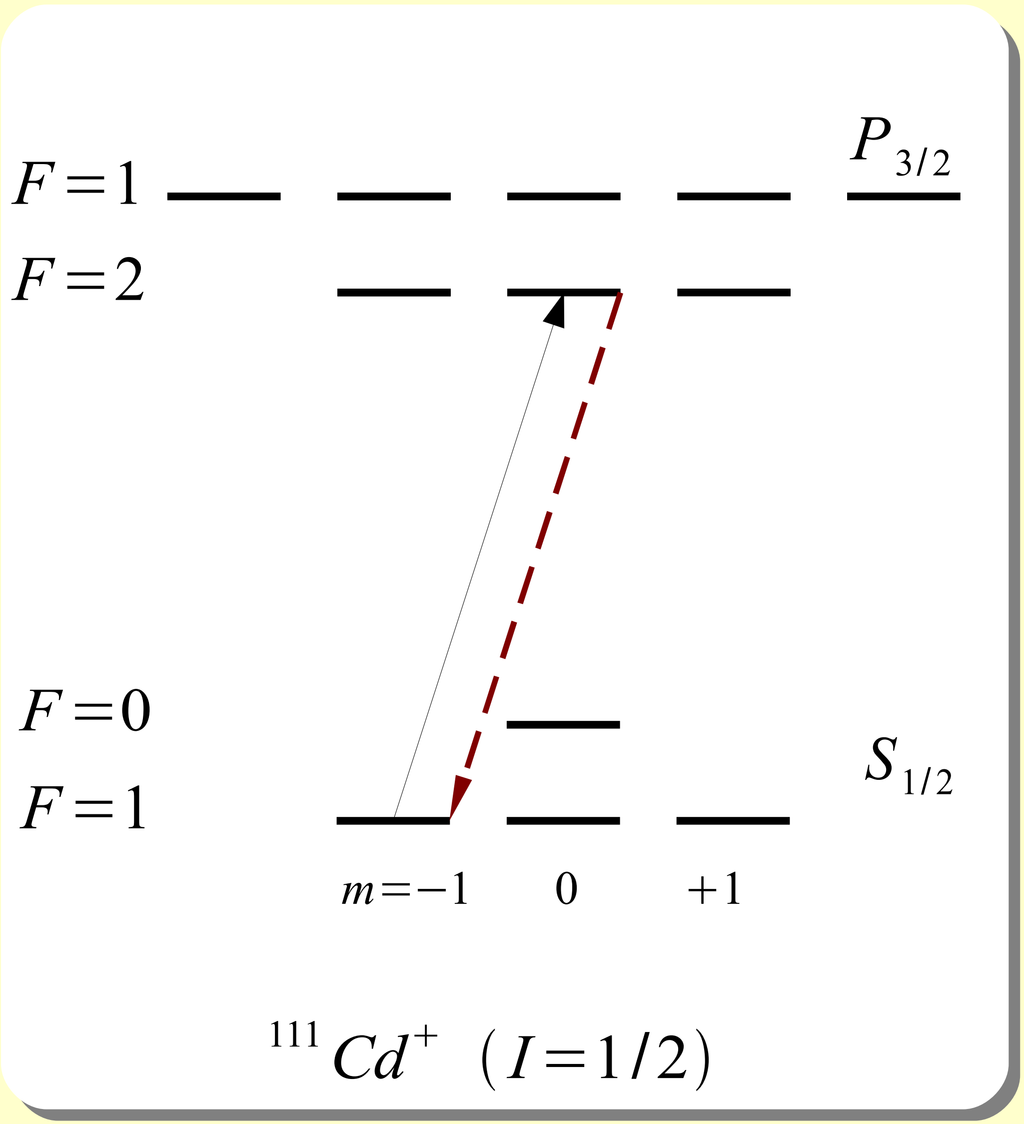
- We have to consider the incoming light as "classical" coherent beam.

$$a|\alpha\rangle \propto |\alpha\rangle$$

Rabi oscillations



- Not useful for doing qubit gates: Light and atom are **entangled**.
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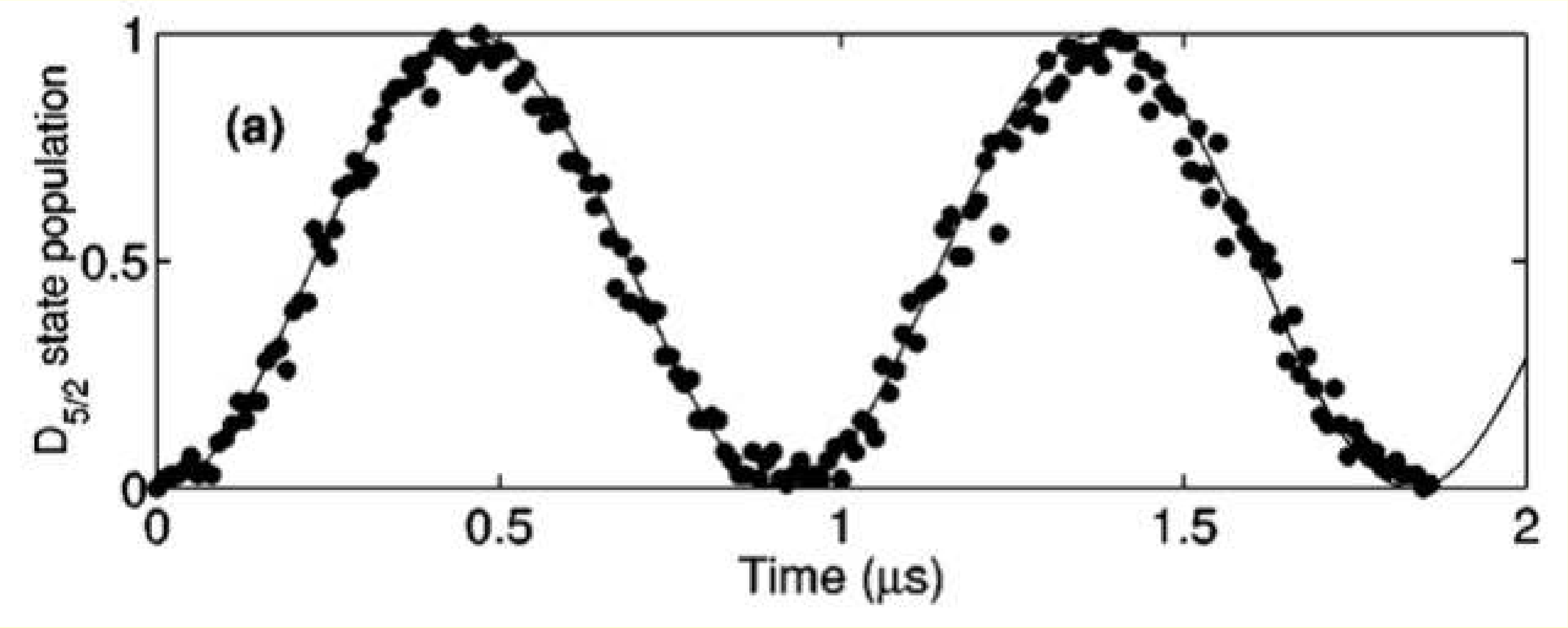
$$a|\alpha\rangle \propto |\alpha\rangle$$

- But using resonant processes means the atom can **decay!**

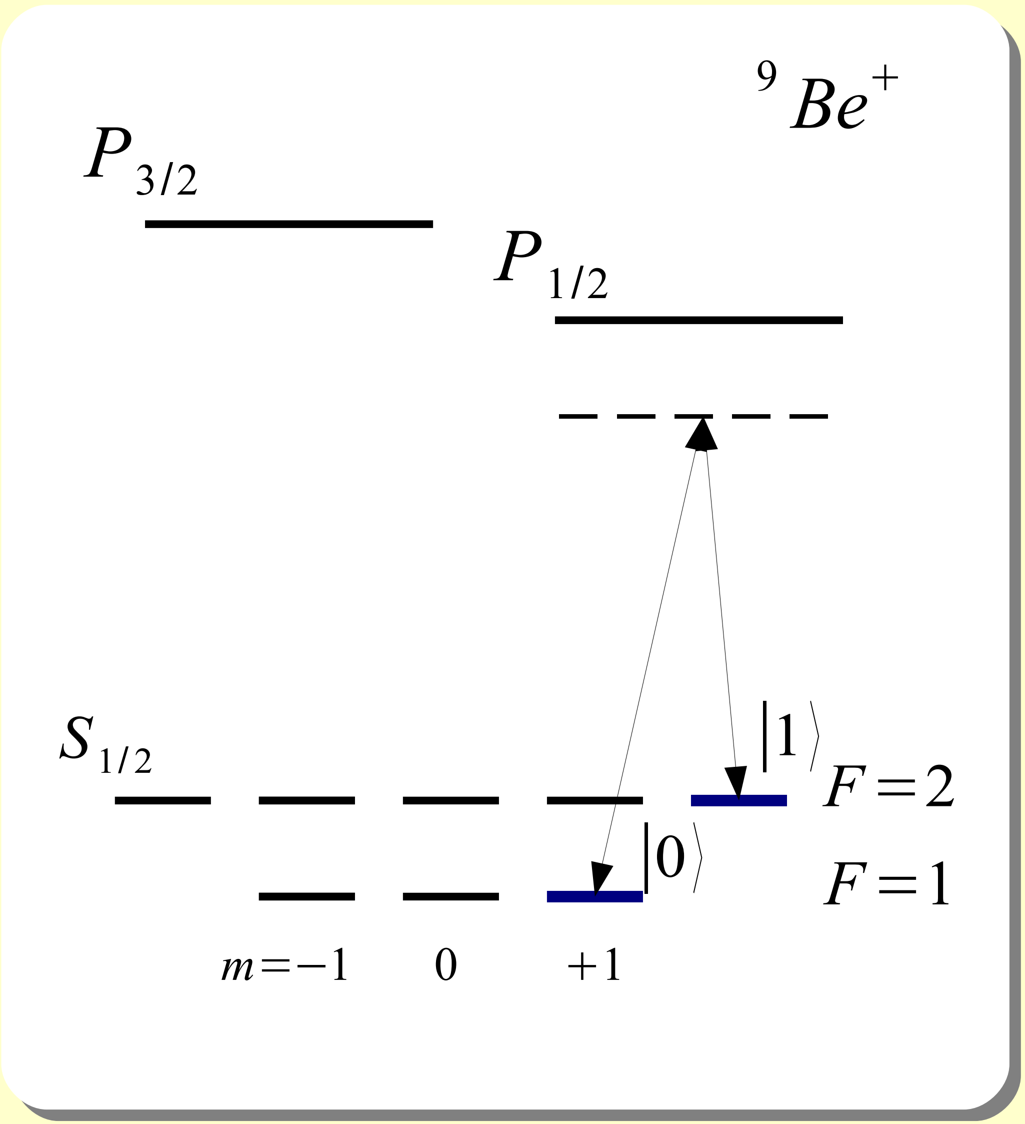
Rabi oscillations



- Rabi oscillations for a trapped Ca ion

A. Steane et al, *Speed of ion-trap quantum-information processors,* Phys. Rev. A **62**, 042305 (2000).

Raman transitions



- When the light is largely detuned (**off-resonance**)

$$\delta = \omega_l - \omega_a \gg \Omega$$

  we have to consider second order processes.

- The effective Hamiltonian may include coupling between hyperfine levels

$$H_{eff} \sim \hbar \frac{\Omega^2}{\Delta} \left(|1\rangle\langle 0| + |0\rangle\langle 1| \right)$$

$$+ \frac{E_{hfs}}{2} \left(|1\rangle\langle 1| - |0\rangle\langle 0| \right)$$

Arbitrary unitaries

- With this Hamiltonian we have enough to perform **any** single-qubit rotation

$$H_{eff} = \hbar \frac{\Omega^2}{\Delta}\left(|1\rangle\langle 0| + |0\rangle\langle 1|\right) + \frac{E_{hfs}}{2}\left(|1\rangle\langle 1| - |0\rangle\langle 0|\right)$$

identify Pauli operators

$$H_{eff} = \hbar \frac{\Omega^2}{\Delta}\sigma_x + \frac{E_{hfs}}{2}\sigma_z$$

Both Ω and E_{hfs} can be tuned by changing the laser intensity and applying magnetic fields.

- H, S, Z are direct. T requires combining X and Z rotations.